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Analyses of joints and associated neo-tectonic deformation band shear zones in the Siwalik Group of southern Surghar-Shinghar Range, Trans-Indus Ranges, Pakistan

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ABSTRACT: *This study presents field observations on joints and deformation band shear zones (DBSZs) at the southern flank of the Sarkai-Mochi Mar (SMM) anticline, which is the southern most structure of the Surghar-Shinghar Range. The eastern flank of the anticline is eroded to form steep scarps, exposing the high angle trace of the Surghar Thrust (the Dara Tang fault).*

Two joint sets NS/NNE and EW/WNW are observed at the southern flank of the SMM-anticline, where the strike of the strata is about east west. These joints are restricted to the hard sandstone bands of the Dhok Pathan and Nagri formations. Field observations show that NS/NNE oriented joints are compressional and EW/WNW oriented joints are extensional in geometry. The orthogonal relationship of compressional and extensional joints yields rectangular blocks (~15×6cm) in the hard sandstone bands. Minor folds with fold axes and axial planes parallel to the compressional joints (NS/NNE) are not uncommon.

The area also contains two sets of strike-slip DBSZs that cut across the sedimentary strata at high angles. The NS steeply oriented DBSZs are strongly banded (foliated), with mesoscopic dextral sense of movement. These DBSZs are common and well developed on the south-eastern part of the SMM-anticline. The second set with N50^0–60^{0}E orientation comprising incipient tabular DBSZs with sinistral movement, cut across the fabric of the NS oriented DBSZs. The two DBSZs form a conjugate geometry. The frequency of these DBSZs is high close to the trace of the Dara Tang fault. Since, the Dhok Pathan Formation is the youngest lithological unit in the area (~0.8Ma), the presence of both the joints and DBSZs in the upper levels of the formation suggests on-going neo-tectonics in this region.

Based on field evidences, three deformational phases have been suggested for the formation of joints and shear zones. The compressional and extensional joints with a component of folding are formed simultaneously in the first deformation phase. This is followed by the second deformation phase in the form of NS oriented banded shear zones. The third deformational phase is characterized by the N50^0–60^{0}E oriented tabular shear zones, which sinisterly cut the NS oriented banded shear zones at an angle of about 50^0-60^0.

The dynamics of the SMM anticline in the context of regional tectonics suggest that the structure experienced compression from west to east during the fold formation. The southern flank of the SMM anticline, where the strike of the beds is east west, is recognized as the plunging hinge area of the fold. Thus, the east-west oriented beds experienced east-west compression and north-south extension in the form of joints and minor folds. We assume that the origin of both compressional and extensional joints in the Mochi Mar and part of the Qabul Khel areas may be related with the folding of SMM anticline. As the north-south oriented Dara Tang fault (Surghar Thrust) cuts across the sedimentary strata passing at the core of the SMM anticline the DBSZs in the area appear to be dynamically related with this fault.

INTRODUCTION

The study of joints includes many aspects of detailed structural analysis. The origin of joints is correlated with the formation of folds (Cloos, 1922; Willis & Willis, 1934) and faults (Sheldon, 1912) and with basement fractures (Barton, 1933). Interpretation of regional stress direction can be carried out based on systematic joint patterns (Parker, 1942; Anderson, 1951 & Engelder, 1982). In addition, aspects like control on landform development (McGill & Storomquist, 1979) and engineering properties of rocks (Barton, 1973; Wheeler & Dixon, 1980) can be studied on the basis of joints. Price (1966) carried out a comprehensive work on joints and stated that "joints are so common and have been studied widely, yet they are perhaps the most difficult of all structures to analyze".

Excellent exposures of joints and deformation band shear zones (DBSZs) in the sandstone of Pliocene Nagri and Dhok Pathan formations of Sarkai-Mochi Mar (SMM) anticline provide an opportunity to study the possible mechanisms responsible for their origin. Our study entails following objectives:

- *characterization and geometry of joints and DBSZs*
- *structural analysis of joints and DBSZs using standard techniques and graphical diagrams*
- *propose models for their origin*

By using these parameters, one can focus on the conditions of joint initiation and subsequent fracture propagation.

The term joint is exclusively used for compessional and extensional joint patterns, whereas the terms shear zones and DBSZs are alternatively used for NS and N50°-60°E oriented structures in this study.

GEOLOGICAL SETTING

The Surghar-Shinghar Range at the eastern margin of the Bannu Basin is a north-south oriented anticline in the hanging-wall of the Surghar Thrust (Main Frontal Thrust) (Fig.1) (Gee, 1989; Sayab et al., 2001*a*, Sayab et al., 2001*b*). The range is a part of Trans-Indus mountain ranges and apparently the western continuation of the Salt Range (Gee, 1989) displaced by the Kalabagh Fault (Yeast et al., 1984). Regional strike of the range from Qabul Khel to Thatti-Nasrati is north-south dipping to the west with an angle of about 45^0 - 50^0 at the outer limbs to the core of the anticline, respectively. The north-south trending Surghar–Shinghar Range is divisible into two anticlines, Makarwal anticline (Danilchik & Shah, 1987) to the north and Sarkai-Mochi Mar (SMM) anticline to the south (Sayab et al., 2001*a*). These two anticlines are separated by Gulapa-Darsola synformal structure (Sayab et al., 2001*a*). The Makarwal anticline plunges towards the south, where the strike of the beds changes and forms a loop. Lithological units ranging

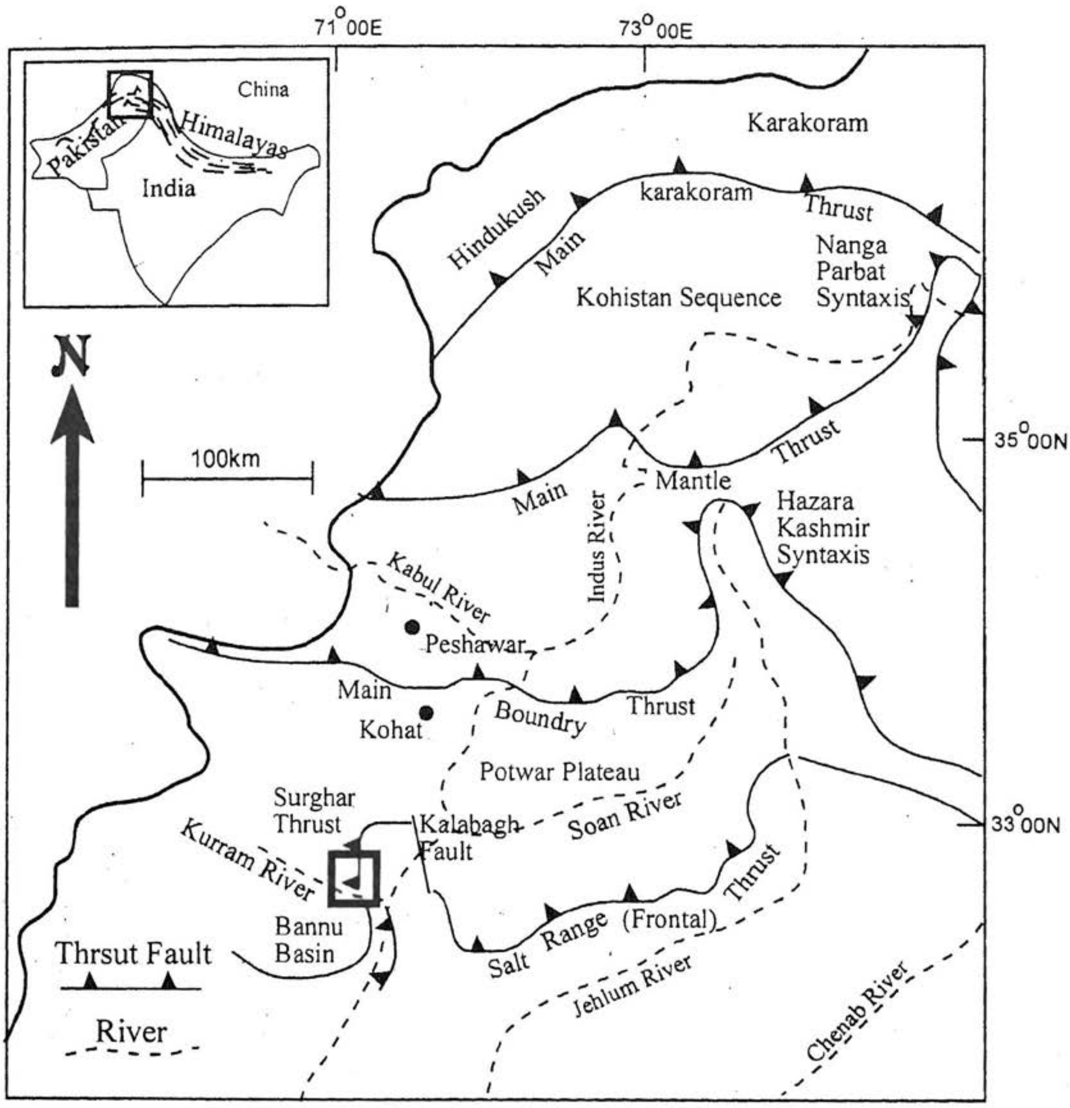

Fig. 1. Outline structural map of northern Pakistan, showing location of the study area.

from Late Permian to Pliocene makeup most of the stratigraphy of the Makarwal anticline. The SMM anticline is a semi-circlular structure predominantly composed of Siwalik sediments with a patch of Mitha-Khattak Limestone in its core.

The eastern flanks of both the Makarwal and SMM anticlines are deeply eroded to form steep scarps, exposing core formations, which are uplifted, overfolded and coupled at places, characterized as the surface trace of the Surghar Thrust (Gee, 1989; Danilchik and Shah, 1987; Sayab et al., 2001*b*). The thrust appears on the geological map of north Pakistan (Searle & Khan, 1996) and on the seismo-tectonic map of Kazmi (1979). Overall, the thrust runs along the eastern margin of the Surghar anticline bringing Punjab foreland alluvium in contact with upper Permian and Mesozoic rocks in the northern (Makarwal anticline), and Neogene rocks in the southern (SMM anticline) parts of the fault trace (Sayab et al., 2001*a*).

MAPPING PROCEDURES

Image Interpretation and Geological Mapping

Edge enhanced Landsat TM (1:65,000) and SPOT (1:50,000) images are used for preliminary mapping of lithological units and structures. The images are especially enhanced by using directional filters for structural interpretations, whereas tonal enhancements are carried out for the identification of lithological units. A tracing of major geological features is prepared from these images, which was used as a base-map for geological mapping on 1:50,000 scale (Fig. 2).

Grid Mapping

A grid map of Mochi Mar and part of Qabul Khel areas has been prepared for detail structural analysis of shear zones on 1:5,000 scale (Fig. 3). This area was selected for grid mapping for its nice exposures of both the joints and shear zones. Theodolite was used for the preparation of grid in the area and for locating and mapping structures.

Circle Inventory method (Davis, 1984)

This method allows a systematic collection of orientation data in a limited area to be used for statistical analysis and frequency diagrams. A circle of known diameter is predetermined on a bedrock surface, where maximum numbers of joints are exposed. Then, the orientation and trace length of each joint within the circle are measured. The measure of joint density is "the summed length of all the joints within an inventory circle, divided by the area of the circle",

$$pj = \frac{L}{\pi r^2}$$

where,
pj = joints density
L = cumulative length of all joints
r = radius of inventory circle

Total six inventory stations were selected using grid co-ordinates (Table 1, Fig. 3), where the geometrical pattern of joints is well exposed and frequency is high. Joint density is calculated for each station and their averages have been re-calculated.

Rose Diagrams

Rose diagrams provide an immediate visual estimate regarding any orientation data. The orientation data collected from the inventory circles is organized into class intervals of 10^0 with respect to the geographical coordinates. Data is then plotted according to the scale by number of joint readings occupy each class interval. Representative frequency diagrams have been shown in Figure 4 (*cf*. Table 1).

TABLE 1. CIRCLE-INVENTORY METHOD FOR EVALUATING JOINT DENSITY IN THE STUDY AREA

Location	Mochi Mar		Mochi Mar		Mochi Mar		Mochi Mar		Qabul Khel		Qabul Khel	
Coordinates	2+26S/10+14E		4+60S/7+80E		4+20W/1+90S		1+85N/3+50E		8+30N/2+40W		5+10N/2+00E	
Formation	Dhok Pathan Fm.		Dhok Pathan Fm.		Dhok Pathan Fm.		Dhok Pathan Fm.		Nagri Fm.		Dhok Pathan Fm.	
Radius of Circle	30cm		30cm		30cm		30cm		30cm		30cm	
Area	$2826cm^2$		$2826cm^2$		$2826cm^2$		$2826cm^2$		$2826cm^2$		$2826cm^2$	
Serial No.	Trend	Length (cm)	Trend	Length (cm)	Trend	Length (cm)	Trend	Length (cm)	Trend	Length (cm)	Trend	Length (cm)
1	NS	45	NS	43	NS	39	$N07^0E$	46	NS	46	NS	40
2	NS	38	NS	37	NS	44	$N05^0E$	33	NS	39	NS	35
3	NS	32	NS	33	$N05E^0$	31	NS	31	$N05^0E$	30	$N06^0E$	16
4	NS	25	NS	20	$N05^0E$	38	NS	35	$N88^0W$	35	$N05^0E$	21
5	EW	10	NS	19	NS	10	NS	34	$N88^0W$	32	$N04^0E$	21
6	EW	09	NS	05	$N85^0W$	10	NS	30	$N88^0W$	33	$N05^0E$	15
7	EW	08	NS	07	$N85^0W$	11	EW	20	$N87^0W$	31	$N05^0E$	22
8	EW	11	$N85^0W$	26	$N88^0W$.	11	$N85^0W$	24			EW	13
9	EW	12	$N86^0W$	25	EW	12	$N87^0W$	22			EW	10
10	EW	09	$N85^0W$	06	EW	13	$N87^0W$	10			EW	04
11	EW	12	$N85^0W$	20	EW	12					$N86^0W$	10
12	EW	15	EW	19	EW	19					$N86^0W$	06
13	EW	12	EW	17	EW	17					$N88^0W$	09
14	EW	11	$N84^0W$	14	$N85^0W$	16					$N87^0W$	15
15	EW	14	EW	09							$N87^0W$	13
16	EW	16	EW	12							$N88^0W$	14
17	EW	16	$N88^0W$	10							$E87^0W$	12
18			EW	12								
19			EW	10								
Cumulative length	C. L.	295	C. L.	344	C. L.	283	C. L.	285	C. L.	246	C. L.	276
Joint Density	J. D. = $0.10cm^{-1}$		J. D. = $0.12cm^{-1}$		J. D. = $0.10cm^{-1}$		J. D. = $0.10cm^{-1}$		J. D. = $0.08cm^{-1}$		J. D. = $0.09cm^{-1}$	

Average Joint Density = $0.09cm^{-1}$

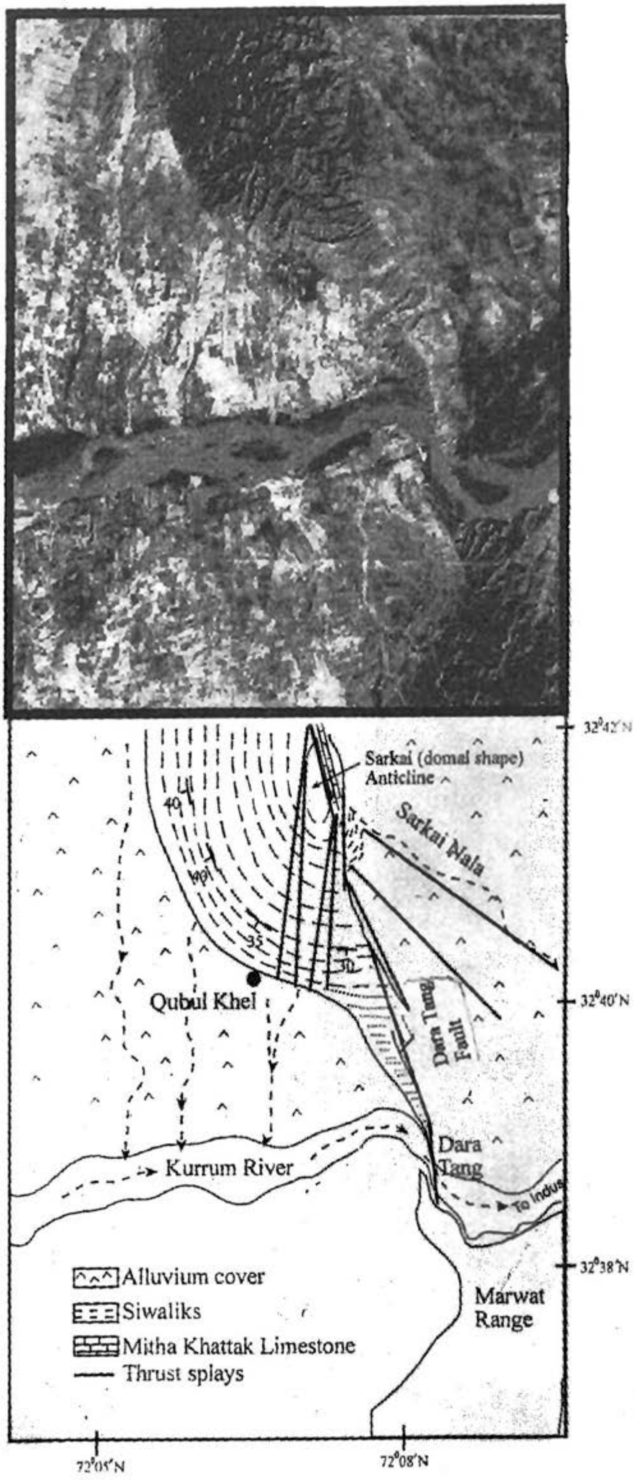

Fig. 2. Edge-enhanced Landsat TM image of the southern most tip of Surghar Range, with some geological interpretation.

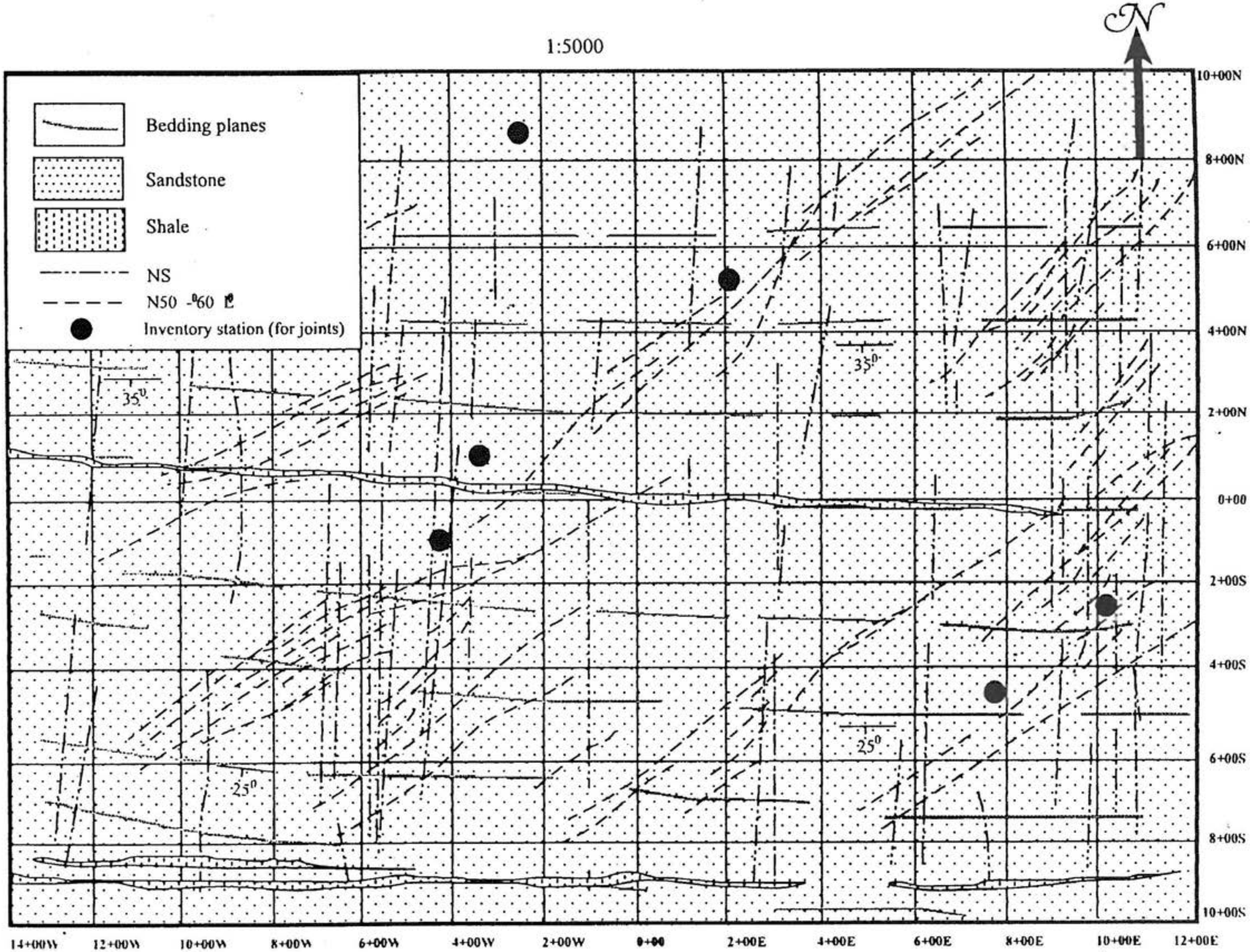

Fig. 3. Grid map of Mochi-Mar and part of Qabul Khel area, depicting geometry of shear zones.

DESCRIPTIVE ANALYSIS

Joints

Joints are fractures along which there has been little or no displacement (Badgley, 1965), that are reasonably continuous and through-going planar fractures commonly on the scale of centimeters to tens or hundreds of meters in length (Davis, 1996). Systematic joints (Hodgson, 1961) display preferred orientation and symmetry. Irregular sets with random orientations are generally categorized as non-systematic (Hodgson, 1961; Kelley, 1959).

Generally, the Nagri and Dhok Pathan formations of the Siwalik Group of the SMM anticline consist of thick sandstone bodies with minor cyclic shale horizons. Within the sandbodies, hard sandstone bands are frequently present. The thickness of the hard sandstone bands generally ranges from few centimeters to maximum of half a meter.

Two sets of joints are observed i.e., NS/NNE and EW/WNW (Fig. 5). These joints are well developed in the hard sandstone bands of the Nagri Formation in general and Dhok Pathan Formation in particular at the southern part of the SMM anticline, where the strike of the beds is eastwest (Figs. 2, 3). The mutual orthogonal relationship/interaction of these joints form rectangular blocks (~15×6cm) of equal dimensions. In the Mochi-Mar area, where the strike of the beds is eastwest, the NS/NNE oriented joints show east-west compression with a component of folding at places (Fig. 6). The fold axes and axial planes are parallel to the NS/NNE oriented joints. The EW/WNW oriented joints show north-south extension (Figs. 5, 6), which are symmetrical and perpendicular to the compressional joints. A maximum 2.5-3cm of joint space or dilation has been noted. The frequency of these joints is maximum at the southern limb of SMM anticline.

Deformation Band Shear Zones (DBSZs)

NS oriented DBSZs are dominant in the Mochi Mar area, close to the Dara Tang fault. These shear zones are strongly banded (foliated) with strike-slip dextral sense of shear. The sense of shear is interpreted from the displacement in the hard sandstone bands (Fig. 7). The second type of shear zones are tabular with N50°-60°E orientation, showing strike-slip sinistral shearing. The sense of shear in this type is interpreted from incipient Riedel fractures developed within the shear zones (Fig. 8). Mainly $\dot{R}_1$, R_2 and Y Riedel fractures have been observed. Displacement along the NS oriented DBSZs is greater than those of tabular N50°-60°E oriented DBSZs, as inferred from the relatively greater amount of strain in the former. The interaction of these incipient shear zones makes a conjugate relationship at an angle of about 60°. The N50°-60°E oriented tabular DBSZs cut sinisterly the main fabric of NS oriented DBSZs and are, thus interpreted to be younger.

STRESS AND STRAIN ANALYSES

Joints

It has been practically established that the principal stress direction (σ_1) will always be parallel to the extensional joint sets and normal to the compressional joints (Davis, 1984; Angelier, 1994; McClay, 1987; Twiss & Moores, 1992). We can analyze our structures under this particular rule, regarding stress and strain analyses of joints.

The general behavior and orientation of joints developed in the Mochi Mar and Qabul Khel area is as under:

- EW/WNW oriented extensional joints *(Je)*,
- NS/NNE oriented compessional joints *(Jc)*,

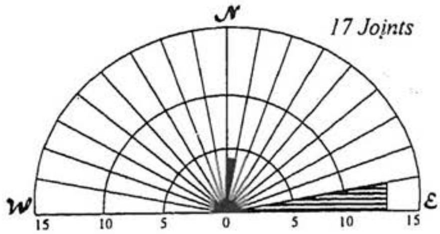

Fig. 4a. Mochi Mar Area

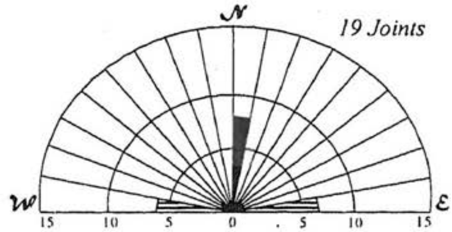

Fig. 4b. Mochi Mar Area

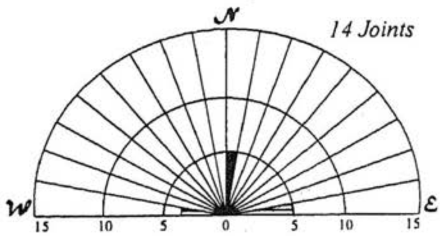

Fig. 4c. Mochi-Mar Area

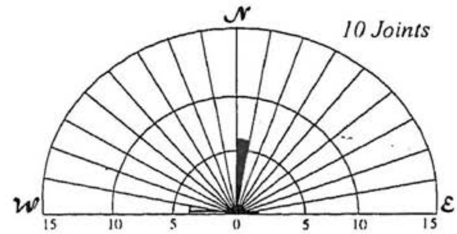

Fig. 4d. Mochi-Mar Area

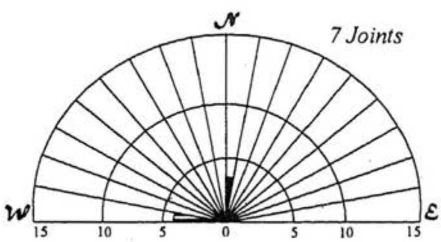

Fig. 4e. Qabul Khel Area

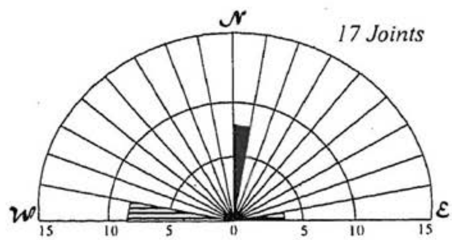

Fig. 4f. Qabul Khel Area

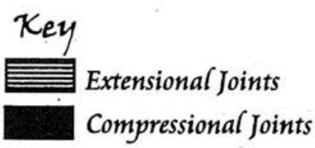

Fig. 4. Rose diagrams of Mochi Mar and Qabul Khel, data obtained from circle-inventory method.

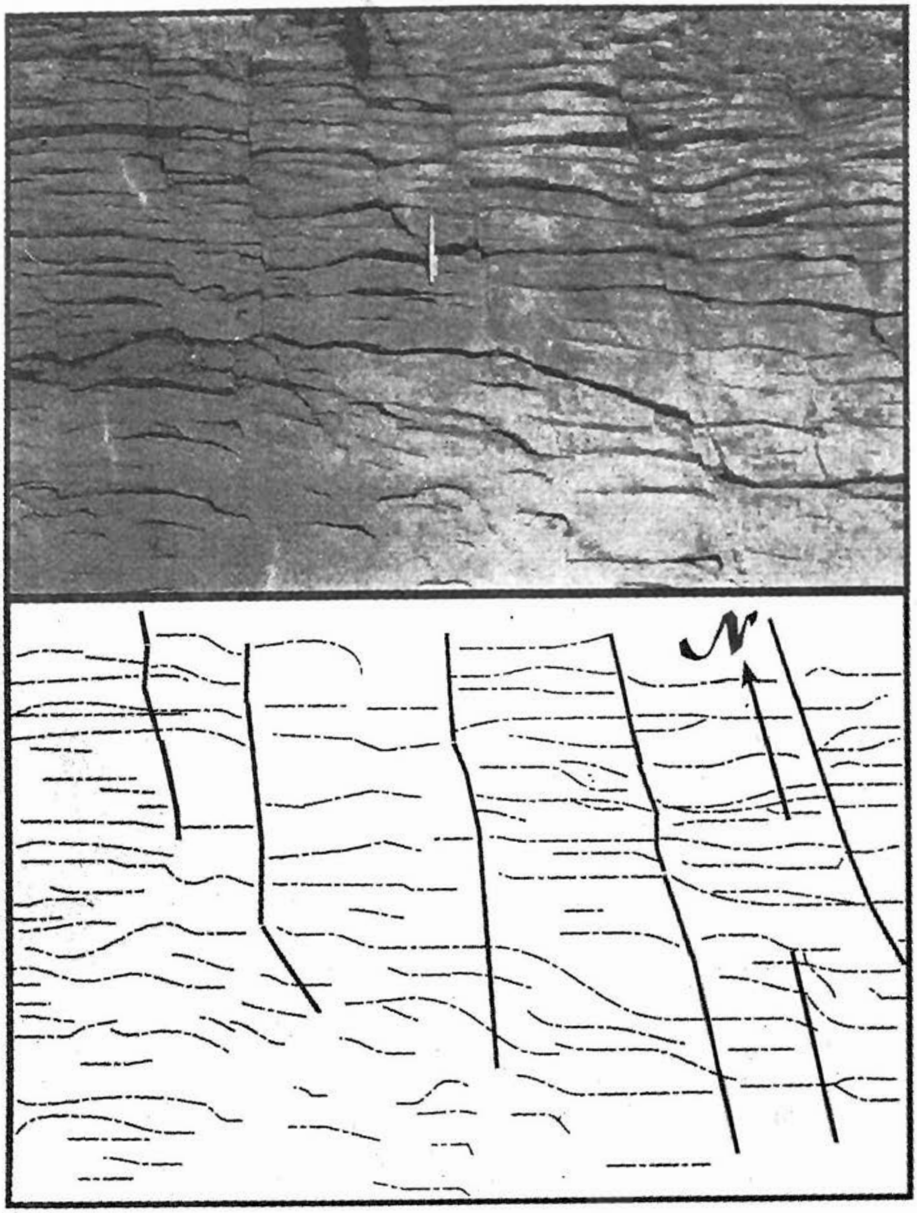

Fig. 5. Oıthogonal joints ın hard sandstone band showing east-west compression (thick line) and north-south extension (dash line) in the Mochi Mar area.

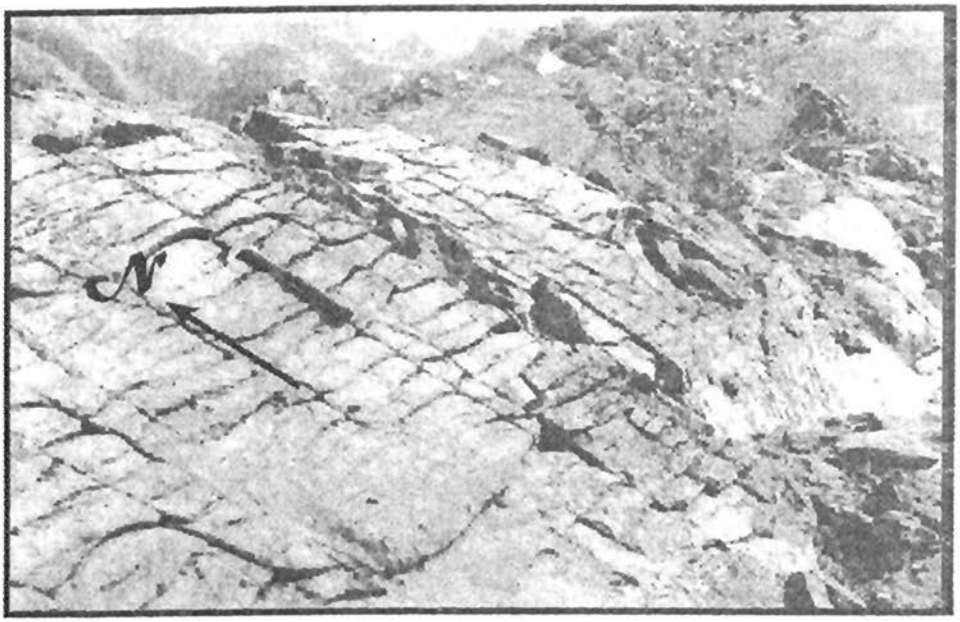

Fig. 6. The axes of the minor folds is parallel to the north-south oriented compressional joints.

Fig. 7. NS oriented deformation band shear zone with dextral sense of shear. Note that the sense of movement is interpreted from the relative displacement in the hard sandstone band; T: towards, A: away

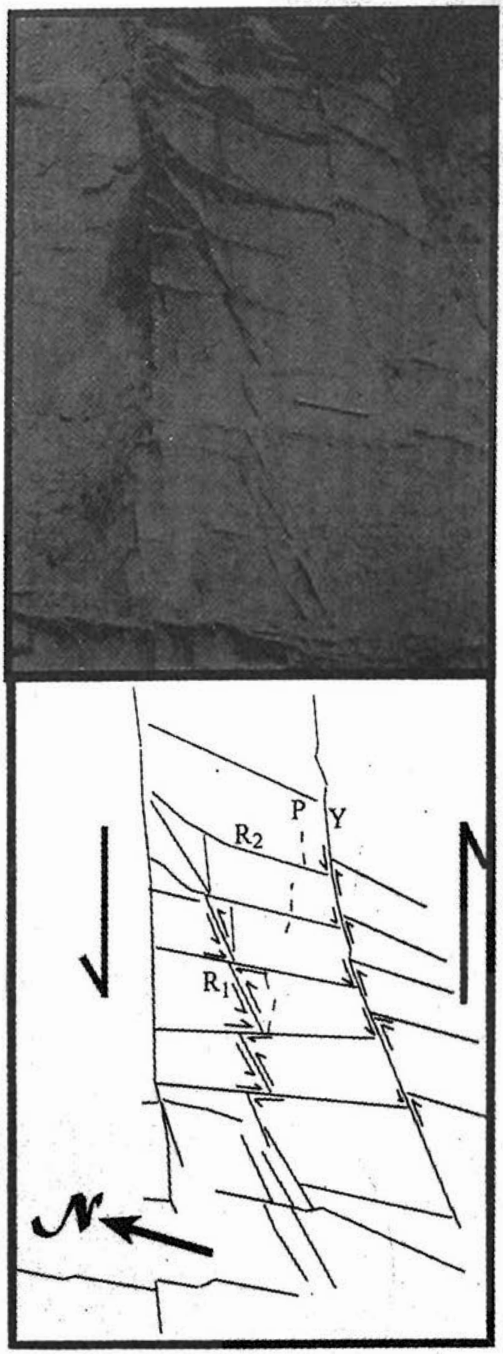

Fig. 8. Riedel fracture pattern in N50°E oriented DBSZ, Qabul Khel area.

North-south oriented minor folds *(fm)*, with fold axis parallel to the compressional joints set.

The orthogonal relationship of *Je* and *Jc* suggests that *Jc* is normal to the principal stress direction (σ_1), accommodating shortening with a component of minor folding, whereas *Je* contemporaneously accommodated dilation. Thus, there is a force responsible for the formation of these systematic and orderly-arranged joint sets. According to our interpretations, these joints with a component of minor folds may have formed due to the principal stress related with the formation SMM anticlinal fold. We have the following reasons for that:

- The southern flank of the SMM anticline i.e., the Mochi-Mar and part of the Qabul Khel are recognized as the plunging hinge area of the fold
- The fold axis of the SMM is about NS, therefore, the structure experienced an east-west compression during the folding,
- As a result of uplifting and erosion, the east-west oriented strata in the plunging hinge area experienced a phase of compression with the formation of compressional (NS/NNE) and extensional joint (EW/WNW) sets.

Deformation Band Shear Zones (DBSZs)
Descriptive analysis of shear zones (NS and N50°-60°E) show that both the sets cut across the bedding as well as the joint surfaces. This indicates that the formation of shear zones is a later phenomena developed in the second deformational stage, whereas the joints are developed prior to the shear zones. The third deformational phase within the shear zones is characterized by the development of tabular shear zones (N50°-60°E), which cut sinisterly the NS oriented ones.

The intensity of these shear zones increases close to the trace of the Surghar Thrust, which is passing at the core of SMM anticline in the form of Dara Tang fault (Sayab et al., 2001*a*). Thus, this fault is responsible for the shear fracture initiation and subsequent fracture propagation in the adjacent sandstone bodies (Sayab and Khan, *in* prep). These strike-slip shear zones in the Mochi-Mar area reflect consequences of the neo-tectonic of the Dara Tang fault (Surghar Thrust) in the form of incipient strike-slip splays. The initiation of these incipient shear zones is a subject of multi-phase deformation along the Dara Tang fault (Sayab et al., *in prep*).

The Dara Tang fault is characterized by high-angle reverse fault between the Mitha Khattak Limestone and Chinji Formation, passing at the core of SMM anticline (Fig.9). However, southwards it gradually changes to strike-slip fault, offsetting the Kurrum River before it dies out at the northern tip of the Marwat Range (Fig. 2) (Sayab and Khan, *in prep*).

CONCLUSION

Structural analysis of two sets of joints with associated neo-tectonic shear fractures in the Dhok Pathan and Nagri formations of the SMM anticline constitute the main topic of the present study. The set NS/NNE defines compressional geometry, whereas EW/WNW oriented joints form extensional geometry, both making an orthogonal relationship. NS and N50°-60°E oriented DBSZs are strike-slip in character, which cut across the sedimentary bedding as well as the joint surfaces. The NS-oriented shear fractures are older, whereas the N50°-60°E ones are younger, as inferred from the relative cross-cutting relationship of the two fracture sets. Both the sets form conjugate geometry at an angle of about 50°-60°.

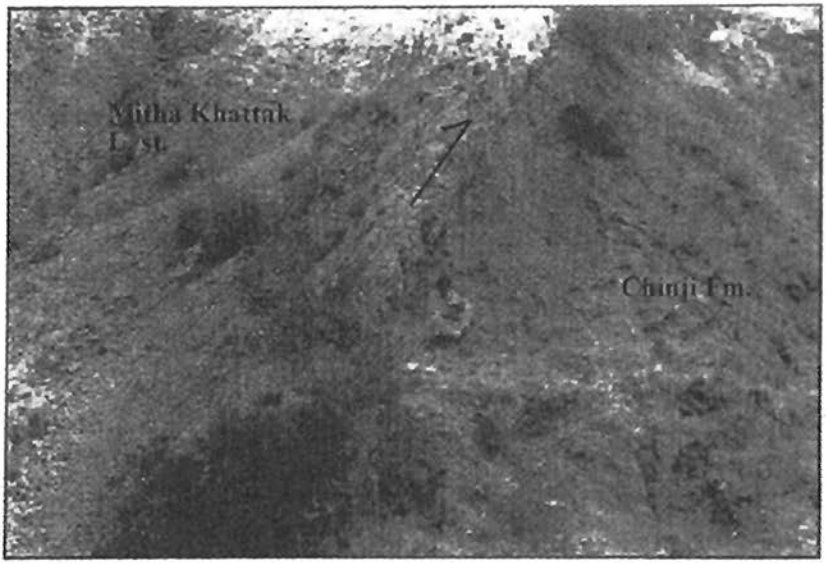

Fig. 9. Sheared reverse slip contact of Mitha Khattak Limestone and Chinji Formation photograph taken from one of the south-eastern Nala of Surghar Range.

Detailed structural analysis of the area show that the orthogonal compressional and extensional joints are formed in the first deformation phase, followed by neo-tectonic DBSZs. The presence of both joints and DBSZs at the upper levels of the Dhok Pathan Formation (~0.8Ma; Khan, 1983), indicate on-going neo-tectonics in the area. The tectonics of the area suggests that the folding of the SMM anticline is responsible for the formation of compressional and extensional joints in the plunging hinge area of the fold, while the shear zones are associated with the dynamics of the Dara Tang (Surghar) fault. Thus, compression in the form of compressional joint sets and tension in the form of extensional joint sets with a component of strike-slip shear zones further suggests that the area seems to be under a phase of transpressional tectonics.

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